Development of Sustainable Supply Chain Models Reducing Carbon Emission using Optimization Techniques

A

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BY

DEEPAK CHANDOLA

(Enrollment No: RSITS230026)

Under the Supervision of

Dr. Mukul Jain
(Supervisor)
ICFAI University, Dehradun
&
Dr. Mukesh Kumar
(Co-Supervisor)
Graphic Era University, Dehradun

ICFAI Tech School
The ICFAI University, Dehradun
2025

The ICFAI University, Dehradun

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I, **Deepak Chandola** declare that the synopsis entitled, **"Development of Sustainable Supply Chain Models reducing Carbon Emission using Optimization Techniques"** being submitted in the partial fulfillment of the requirement for the award of the degree of Doctor of Philosophy in **Mathematics** under ICFAI Tech School, The ICFAI University Dehradun, during the academic year 2025-26.

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Candidate's Name: Deepak Chandola

Enrollment No: RSITS230026

The ICFAI University, Dehradun

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Signature of the Co- Supervisor in full
Name in Capital Letters: Dr. Mukesh Kumar
Designation & Address: Professor, Department of Mathematics, Graphic Era (Deemed to be University) Dehradun, Uttarakhand.

Signature of the Supervisor in full
Name in Capital Letters: Dr. Mukul Jain
Designation & Address: Assistant Professor, The ICFAI university, Dehradun. Uttarakhand.

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Course of Study	Ph D. (Mathematics)
Name of Guide	Dr. Mukul Jain & Dr. Mukesh Kumar
Department	ICFAI Tech School
Acceptable Maximum Limit	10
Submitted By	research@iudehradun.edu.in
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Table of Contents

S. No.	Description	Page No.
	Prelim pages (Candidate declaration, Certificate, Plagiarism report, List of tables and figures, & Abstract) ……	I-VI
1. 1.1. 1.2. 1.3.	Introduction…… Supply chain…….. Carbon emission ……... Sustainable inventory models ……...	**1-8** 2-3 3-4 4-8
2. 2.1. 2.2.	Literature review…… Bibliometric analysis …… Articles related to literature review ……...	**8-18** 13-16 16-18
3.	Supply chain models utilized in existing research……	19-20
4.	Research gap……..	21
5.	Research objective……	21
6.	Research methodology……..	22-23
7.	Significance of proposed work……	24
8.	Work plan……	25
9.	References……	26-34

List of Tables:

Table 1	Detailed description of research papers ……	14
Table 2	Research papers distribution…….	16
Table 3	Articles related to literature review……	16-18
Table 4	Supply chain models utilized in existing research…….	19-20

List of Figures:

Figure 1	Inventory flow chart……..……..	1
Figure 2	Cost effectiveness of different energy production sources…….	5
Figure 3	Global greenhouse gas emission from different economic sectors…….	7
Figure 4	Research papers finding (Scopus database) ……..	13
Figure 5	Topic wise trends of research papers by R-Studio…….	14
Figure 6	Author wise trends of research papers by R-Studio ……..	15
Figure 7	Journal wise trends of research papers by R-Studio ……	15
Figure 8	Research methodology flow chart…….	22

Abstract:

Supply chain management (SCM) has been evolved significantly which integrate sustainability of supply chain, technological innovations and refine optimization techniques. In early time of globalization SCM focused on few ways like supply of raw material from one place to another and finished goods from factory to consumer but nowadays SCM includes border goals like social dimension, economic and environmental. In today modern supply chain Closed loop SCM include manufacturing of new products and promote recycling of old product which will help to get sustainable goals and provide extra economic benefits. Calculation of carbon footprints and carbon emission is common in nowadays which is helping companies to calculate carbon footprints by their production and promoting less carbon emission techniques among manufacturers. SCM procedures have been further improved by technological advancements. Real time networking, data interchange and decision making are made possible by the predictive maintenance system. In order to develop sustainable supply chains model that lower carbon emission while retaining efficiency, optimization approaches are essential. Modern techniques like heuristic algorithms and multi-objective optimization aid in striking a balance between environmental and economic objectives. Policy makers and businesses looking for more environmentally friendly solutions can learn a lot by comparing models with and without emission restriction.

Keywords:

SC- Supply Chain**,** SCM- Supply Chain Management, SSCM- Sustainable Supply Chain Management, CLSC- Closed-loop Supply Chain**,** EOQ - Economic Order Quantity, CE- Circular Economy, SDGs- Sustainable Development Goals, MCDM- Multi Criteria Decision Making. RE- Renewable Energy, GEP- Gross Environmental Product

1) Introduction:

In a business setting, keeping and maintaining an inventory is a mutually beneficial process. Inventory is the gathering of products, raw materials and other essential resources required for the production or manufacturing of goods and services explained by Alfalla-Luque, Prashanta Kumar., et.al. (2013). However, its management needs to be proactive, accurate, and effective. Long-term overstocking raises high expenses, spoilage and obsolescence risk, theft risk, demand swings, dead stock buildup and financial resources blockages. On the other side maintaining inadequate inventory can lead to stockouts, lost sale opportunities and probable damage to the company's reputation and customer satisfaction.

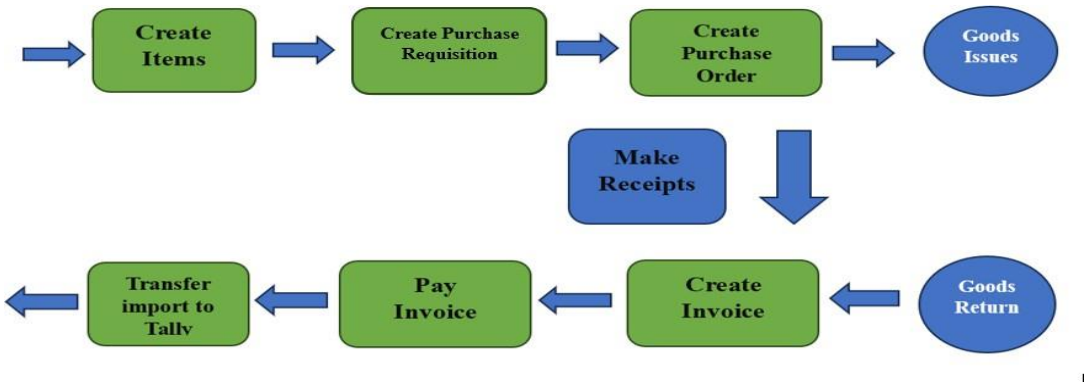

Figure 1: Inventory flow chart

Analyzing a company inventory turnover rate during a specific time period is one way of evaluating its success. Business houses can cut-short their storage expenses and increase

profitability by selling their stock more quickly comparing to rivals. By increasing sales processes, such efficiency frequently gives a competitive advantage (Figure 1).

In general, inventory levels fall over time until the next production or resupply cycle occurs, either because of client demand or owing item deterioration, leading to what is referred to as declining stock illustrated by Marchi, Zanoni., et.al. (2023). Such deteriorating items can typically be classified into two categories, depending on the nature and rate of deterioration. Products that naturally deteriorate or lose their usefulness gradually as a result of spooling, decay, evaporation or expiration fall under the first group. Fresh meat, fruits, vegetables and medications are common examples. Products that lose value owing to technology developments or the emergence of alternatives rather than physical deterioration fall into the second group. This category includes things like smartphones, computer chips, fashion accessories and seasonal clothing. For example, during a period of popularity the iPhone 16's market value declined. This loss was mostly caused by changing consumer preference and replacement of new iPhone model 17.

1.1. Supply chain:

A supply chain (SC) is a complete process of from creating and delivering a good or service, it starting with the procurement of raw materials and ending with the delivery to end-users explained by Chandra, Charu., et.al. (2007). A supply chain is a collection of interconnected components that work together to convert raw materials into finalized goods and services. Supply chain process starts with the exchange of information, followed by the consumption of natural resources, human resources is also an important component which provide labors for production and other operational duties. The main player of supply chains are manufactures, who produce things, suppliers of raw materials, warehouses using to hold the stocks, transport

to move the goods from one place to another place and distribution centers and distributors. These setups work together and create a robust structure which help products to reached up to end customer. Supply chain mainly includes production, transportation and distribution related activities explained by Taghikhan F., Voinov, et.al. (2021). However, in the dynamic world growing environmental requirement are causing major shifts in operating strategy and production processes. The idea of SSCM emerged as a result of companies prioritizing ecofriendly supply chain strategies. SSC seek to strike a balance between ecological growth, in contrast to conventional models that only consider cost and efficiency. The aim to save natural resources for the coming generations while meeting present market demand. This strategy ensures that economic expansion does not come at the expense of environmental damage by integrating environmental considerations at every level, rom the procurement of raw materials to production, distribution and delivery. By implementing greener practices, businesses may meet the increasing demand from customers for ecologically friendly products while also building long-term resilience and complying with regulations.

1.2. Carbon emissions:

Since the release of carbon dioxide has caused many environmental problems, so government are trying to control carbon emission on priority basis. Many inventory system actions, including acquiring, warehousing, and moving commodities, result in carbon emissions. As a result of this governments applied restrictions to limit emissions in inventory systems and build sustainable supply chain. Inventory management under carbon emission policies refers to organizing and optimizing inventory-related processes within an organization while adhering to governmental regulations and internal procedures to mitigate carbon emissions and reduce environmental impacts. Inventory management under carbon emission can lead to significant

supply chain resilience, cost saving and enhanced brand reputation in addition to fostering environmental sustainability. It shows a dedication to minimizing the adverse environmental effects of inventory management procedures and helps to create a supply chain that is more environmentally friendly and sustainable. Here is an explanation of what it entails efficient transportation. The transportation of goods and manufactured items is a main source of carbon emissions. Carbon-conscious inventory management emphasizes optimizing transportation routes using low emission vehicles and consolidating shipments to minimize the carbon impact of transportation. Sustainable packaging to cut carbon emissions eco-friendly packaging materials and techniques must be used. Recyclable or biodegradable packing materials for example lessen environmental effects while simultaneously reducing trash.

1.3. Sustainable inventory models:

The initial set of models for inventory management was developed to assess how much of a given lot size would be required to meet needs at the lowest possible cost. As a result, the main emphasis of these models is on determining how much to get and when to order it. For example, the traditional EOQ model doesn't take environmental issues into account and instead concentrates on economic concerns. However, in addition to financial efficiency, Environmental issues have grown in importance for enterprises in recent years explained by Taleizadeh, Ata Allah, et.al. (2018). In the context of sustainable development, green inventory system reduce carbon emission are essential for promoting economic growth. Using sustainable inventory management tools can give you benefits such as tax reduction, revenue growth, cost reduction and environmental outcomes. Adopting sustainable supply chain lessening ecological footprints and promote economic growth and protect natural resources for future generations.

SSCM have achieved a global presence in the role of address environmental sustainability, energy sustainability and cost effectiveness of the supply chain and the end product illustrated by Federica, et.al. (2013). While carbon emissions are becoming a global concern, SSCM has been thoroughly studied in the literature to construct a concept connected to sustainable supply chain management, and emerged as a way to move into the green economy by creating a green supply chain. The decrease in the use of fossil fuels due to their future cost-effectiveness and greenhouse gas emissions is the main force behind this shift. The cost of producing green energy is steadily declining as it becomes more and more necessary for the average person, and this trend will continue in the future (Figure-2).

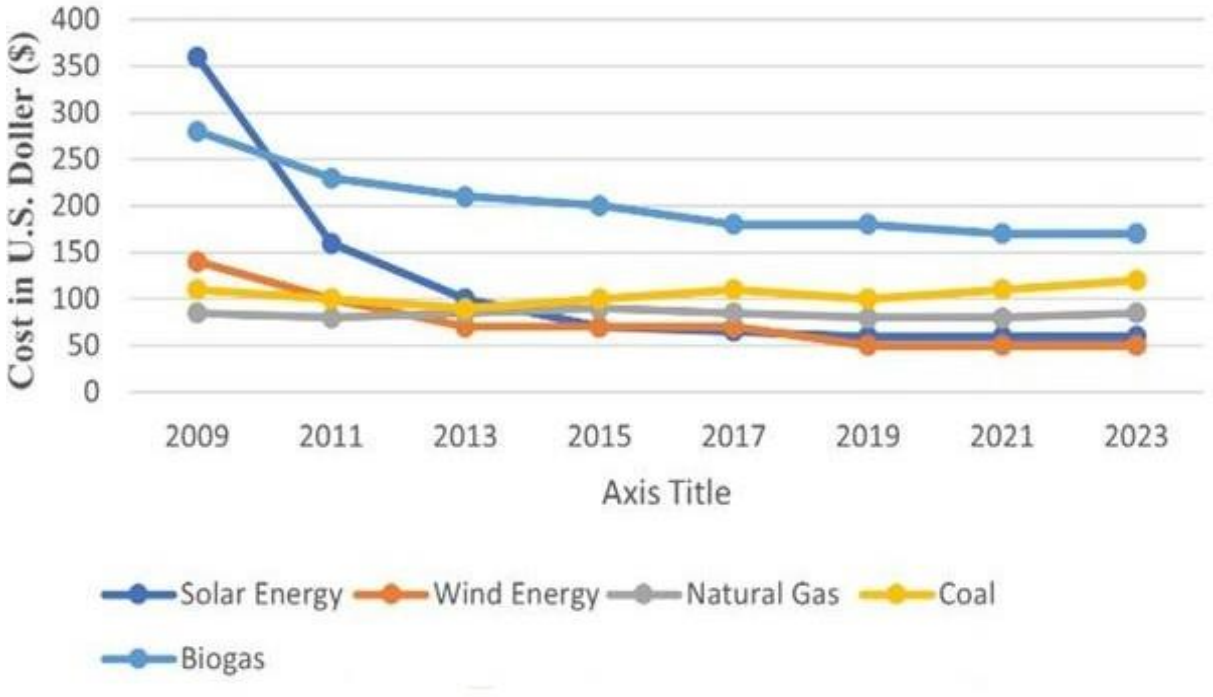

Figure 2: Cost effectiveness of different energy production sources

Performance evaluation and integration of activities with regard to environmental impact, economic profit or loss, and social impact of the supply chain (SC) are the main goals in the field of SSCM. Since supply chain (SC) can have a important impact on a region's economic development, including sustainability principles into SC is essential to promoting SSCM. Coordination of resources, assets transfers, and a strong dedication to sustainability goals are important for the establishment of an efficient SSCM system. In the context of RE, this means highlighting how SSCM may offer affordable energy substitutes that reduce reliance on traditional sources and consequently, carbon emission. RE system are frequently assessed using LCA with an emphasis on their effects on the environment explained by Paraskevopoulou, Christina, et.al. (2022). LCA methos generally used to predict the impact of a production on the environment but LCA alone cannot fully calculate the closed connection within the supply chain. This required some new techniques and models to calculate how much exactly production of a particular product will affect our environment and what will be the economic and social impact of this. Many AI tools is now fulfilling the demand of companies by processing of maximum number of data, suggesting best way to improve supply chain and mitigating the impact of production on our environment. AI is improving customer satisfaction level, reduce cost of production, improve performance and increase efficiency during the

complete supply chain. This helps business to reduce the risk of stockouts and overstocking, optimize inventory models and improve supply chain processes.

AI promotes sophisticated levels of supply chain automation through these applications, supporting environmental goals while preserving competitiveness. The complexity of using AI in renewable energy in supply chain with conventional energy infrastructure is data integration, intermittency, supply chain dynamics, uncertain market condition, regulatory compliance, geographical consideration, infrastructure compatibility, cybersecurity, skill gap etc. Despite all these complexities, leveraging AI in renewable energy supply chain offers many benefits including, improvement in efficiency, reduce cost, and reduce carbon emission to increase sustainability in SSCM. These challenges need cooperations among stakeholders, investment in research and innovation, continuous advancement in AI applications.

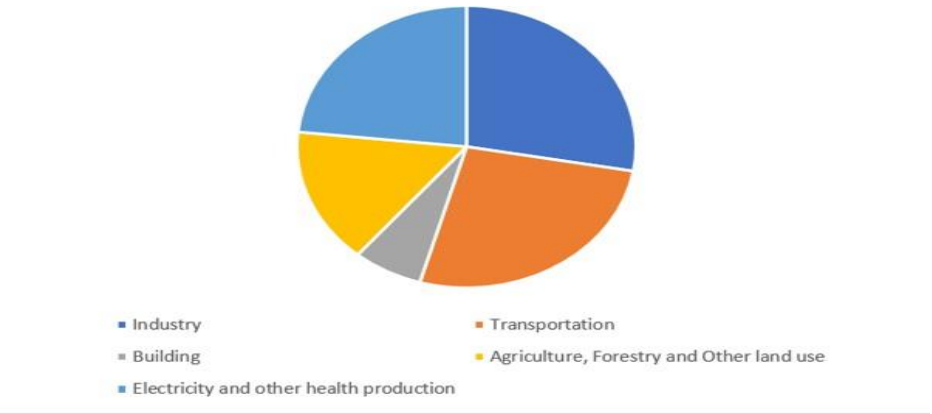

Figure 3: Global greenhouse gas emission from different economic sectors

This paper conducts a detailed assessment of Renewable Energy (RE) from a SSCM perspective calculating the values and constrains of each point in the SC. This study objectively analyses the five main components of the RE ecosystem: The RE and RE supply chain, RE performance, carbon emission during supply chain, barriers and strategies associated with SC development, and use of a predictive analytical tool in SSCM (Figure 3).

2) Literature review:

Supply chain (SC) appeared for the first time in literature when Oliver & Webber (2012) first time proposed the definition of management of such systems. Since then, Supply chain management (SCM) area has grown considerably both at research and industrial levels. With the advent of new technologies, the environmental impacts of development have become a concern for quite a long time now. In order to tackle this problem, Guide Jr. & WassenhoveL.N., (2002) suggested a closed loop supply chain (CLSC), whose planning, execution, and design are all focused on optimizing value creation throughout a product's life cycle. Savaskan & Wassenhove L.N., (2006) emphasized the advantages of integrated (CLSC) systems, and other published publications further examined these systems such as Salema, Novais, (2010) and Zeballos, Méndez, et.al. (2014). Researchers now faced a problem of implementing sustainability to the industry to incorporate the economic and social aspects as well. The definition of corporate social responsibility (CSR) often advocates ethical behavior with respect to these systems. Hutchins & Sutherland (2008) reviewed metrices frameworks and indicators of social impacts and actions in relation to their capacity to support supply chain. The scope of this study has been widening to include on only the economic and environmental concerns but also the social concerns as explored by Barbosa-Póvoa, Carvalho, A., (2018).

Seuring & Müller, M., (2008) introduced performance indicators and social aspects to the traditional (SC) and extended the study and took a broad look at (SSCM) and the issues emerging in this field and provided a conceptual framework of the existing research in the field.

The carbon footprint (CF) serves as an important indicator for assessing the extent to which nations, industries, and individuals contribute to overall environmental sustainability. The carbon footprint (CF) encompasses the carbon emissions (CE) generated through consumption activities across global supply chains for goods and services. In their analysis of Indian households, cities, and regions, Lee, Taherzadeh, O., et.al. (2021) highlighted the importance of recognizing individual responsibility for climate change, particularly in the formulation of national and international climate policies. Pottier, A., (2022) examined household carbon footprints and estimated their elasticities in relation to income and expenditure patterns. In a different context, Fisher-Vanden, Pitcher, H.M. et.al. (1997) investigated the role of carbon taxes and tradable permit policies in India, analyzing their potential implications for the national economy. Ghosh, S., (2010) argued that, in the long run, prioritizing the use of renewable energy sources can effectively reduce carbon emissions without constraining a country's economic growth. Arouri, Youssef, et.al. (2012) studied energy consumption and economic growth and found out that carbon dioxide (CO_2) emission reductions have been achieved even while exhibiting economic growth over a certain period. Soytas, Ewing, B., et.al. (2007) investigated energy consumption, income and carbon emissions, inclusion labor and gross fixed capital formation in their model. Data and information exchange plays a great role in modern SSC. Originally initiated in industrial revolution, focuses heavily on interconnectivity, automation, machine learning and real-time data. Suhi, Enaye, R. et.al.

(2019) conducted a comprehensive review and presented an overview of the content, scope and findings of Hafezi & Zolfagharinia, H. (2018) analyzed the driving and dependence power of barriers to adopt in Indian manufacturing industry using interpretive structural modeling (ISM). Singh, P. & Srivastava, R. (2021) explained a new stage of industry where businesses can attain improved industrial performance through product connectivity and the integration of vertical and horizontal manufacturing processes. The anticipated contribution of technologies to industrial performance illustrated by Gutierrez, Rabelo, L. et.al. (2021). Boukherroub, Ruiz, T., et.al. (2015) further generated a methodology for evaluating the social acceptability of technology for the advancement of digital manufacturing (DM). An empirical examination of benefits, challenges and critical success factors of in manufacturing and service sector was taking the real-world applications into consideration. An analysis of almost 100 definitions and related concepts, and limitations of research comparability was addressed by Culot, G., Marco, et.al. (2020). Potential avenues for increasing efficiency flexibility, productivity, cybersecurity, product and service quality, and data-driven decision-making were studied by Dalmarco; G. Ramalho et.al. (2019) with reference to readiness in manufacturing companies was studies by Machado, Winroth, M., et.al. (2019) by assessing seven businesses' level of digital readiness using a self-assessment form and then conducting a case study to find the factors that encourage, hinder, and facilitate digitalization. Duman & Akdemir, B., (2021) explored how technological components influence organizational performance, particularly highlighting the barriers faced in implementing advanced technologies across manufacturing sectors in both developed and developing economies. From a similar angle, Govindan, k. & Devika, K. (2014) looked at how companies use technology to implement process innovation strategies, emphasizing the combination of green supply chains with lean methods. In the

context of disassembly and remanufacturing processes explained by Koberg, E. & Longoni, K., (2019). New research and technologies are playing important role in recycling of products, designed a network-based system to predict maintenance in the supply chain. In today digitised and modern supply chain management world Radio Frequency identification (RFID) is becoming important technology. RFID is improving supply chain management by reducing inventory cost, improving information accuracy on real time, cutting short process time and making more efficient supply chain as shown by Savaskan & Wasenhove, L.N. (2006). Ni, L.M., Zahang, D., et.al. (2011) explained how RFID can provide low cost and easy to track system which will provide real time location as well. Hahnel & Burgard, W., (2004) explain how we can improve real time mapping and data localization. Tajima, M. (2007) provides an explanation how RFID provide companies a competitive advantage. In addition, Michael & McCathie, L. (2005) evaluated the benefits and drawbacks of RFID in comparison to conventional information exchange methods and came to the conclusion that RFID offers more efficiency. RFID adoption in a single retailer to supplier supply chain under random demand conditions was further examined by Cui, L., Deng, J. et.al. (2017), who demonstrated how the technology can minimize waste and inventory errors.

A key component of improving supply chain efficacy and sustainability is optimization in order to overcome this difficulty, Shankar, Jason, C.H. et.al. (2013) simultaneously optimized strategic design and distribution choice for a three-tier supply chain that included suppliers, production sites and distribution centers. Zhang, Lee, C.M.K., (2016) developed a multi-objective optimization model for creating supply chain networks (SCN) with various distribution channels, going beyond tradition SCN architectures and integrating sustainability

into strategic decision making. Dutta, Mishra, A. et.al. (2020) improved the sustainability of online retail supply chains in the Indian e-commerce setting by including reverse logistics into a multi-objective optimization framework. By developing a multi-item and multi-objective inventory model that included green investments and took backordered a mount into account illustrated by Ahmadian, A. & Ali, I. (2021) expanded on this line of inquiry. In a similar way, Wang, B. Liang, Y. et.al. (2020) created a framework for downstream oil supply chain optimization that specifically took the emission-cost relationship into account in an effort to strike a balance between environmental performance and profitability. Additionally, optimization models have been frequently used to solve industry- specific issues. In order to optimize perishable food supply chains and lower spoilage while increasing efficiency, Govindan, Devika, K. (2014) developed a two-echelon, multi-vehicle location-routing issues with time windows. In a related field, Lejarza & Baldea (2022) looked at consumer preferences for purchases and suggested an optimization framework for handling various quality variables in supply chains for perishable goods. In order to evaluate and enhance SSC's De Castro Vivas, Freires, F.G.M. et.al. (2020) developed a sustainability evaluation and optimization technique that incorporates analytical and mathematical models. In order to assess the dual credit policy in the passenger car industry at the policy level, Li, D., Manzini, R. et.al. (2014) developed a dynamic optimization framework utilizing a multi- period credit market equilibrium model which highlighted the connection between regulatory frameworks and sustainable supply chain practices by presenting a three-echelon cold chain optimization model that took freshness-keeping efforts under cap-and-trade rules into account.

2.1. Bibliometric analysis:

We looked at the journal's research environmental using R-studio. Co-Authorship, Co-Citation and term Co-Occurrence were among the bibliometric variables used to map the journal's intellectual structure. Key trends in the field, including the most important writers, research objects and the development of science cooperation are highlighted in the generated network visualizations. The edges show connections or co-occurrences between the nodes, which stand for specific articles, writers and keywords. A key search query with optimization technique or mathematical modelling or sustainable supply chain management yielded a substantial 676 relevant scholarly articles founded. This large no of volume of research not only underscore the academic and practical importance of sustainability into supply chain but also highlight the role of mathematics into Supply Chain.

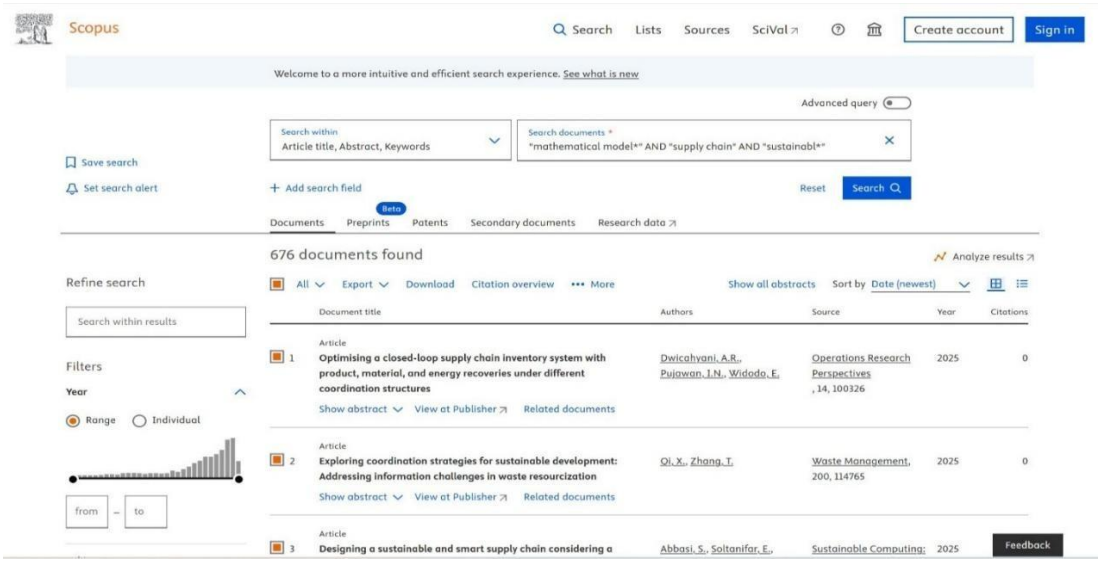

Figure 4: Research papers finding (Scopus database)

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	1995:2025
Sources (Journals, Books, etc)	313
Documents	663
Annual Growth Rate %	12.79
Document Average Age	5.4
Average citations per doc	32.96
References	0
DOCUMENT CONTENTS	
Keywords Plus (ID)	3412
Author's Keywords (DE)	1820
AUTHORS	
Authors	1796
Authors of single-authored docs	40
AUTHORS COLLABORATION	
Single-authored docs	52
Co-Authors per Doc	3.35
International co-authorships %	35.75
DOCUMENT TYPES	
article	498
article article	5
book	5
book chapter	13
book chapter article	1
conference paper	104
conference review	12
editorial	1
erratum	1
review	23

Table 1: Detailed description of research papers (Scopus database)

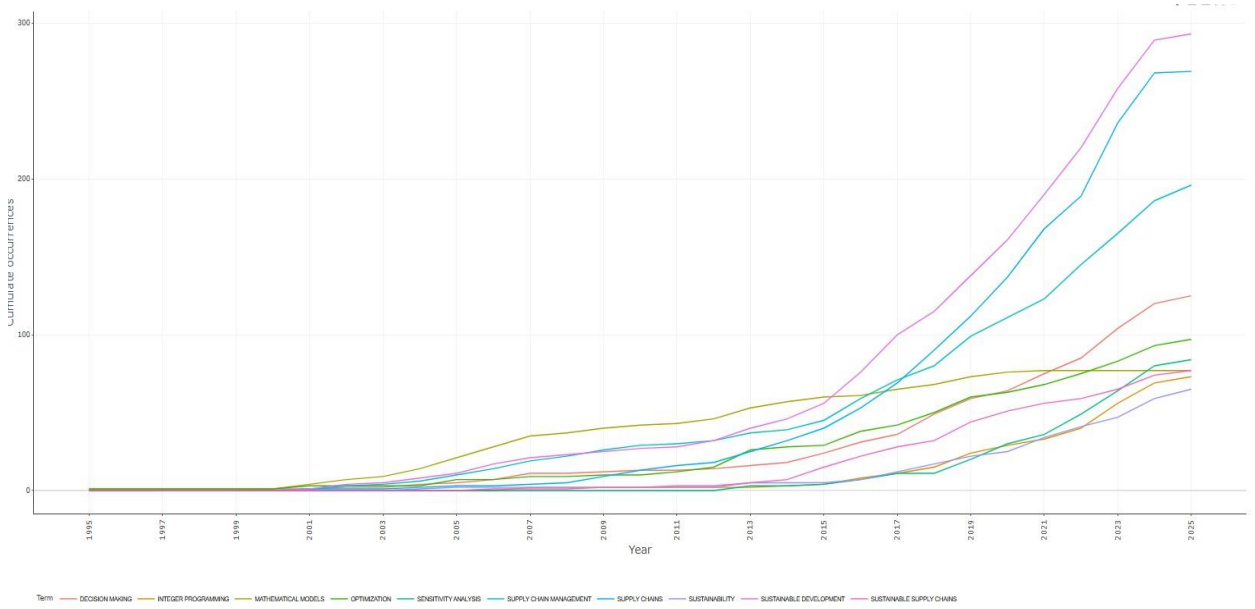

Figure 5: Topic wise trends of research papers by R-Studio

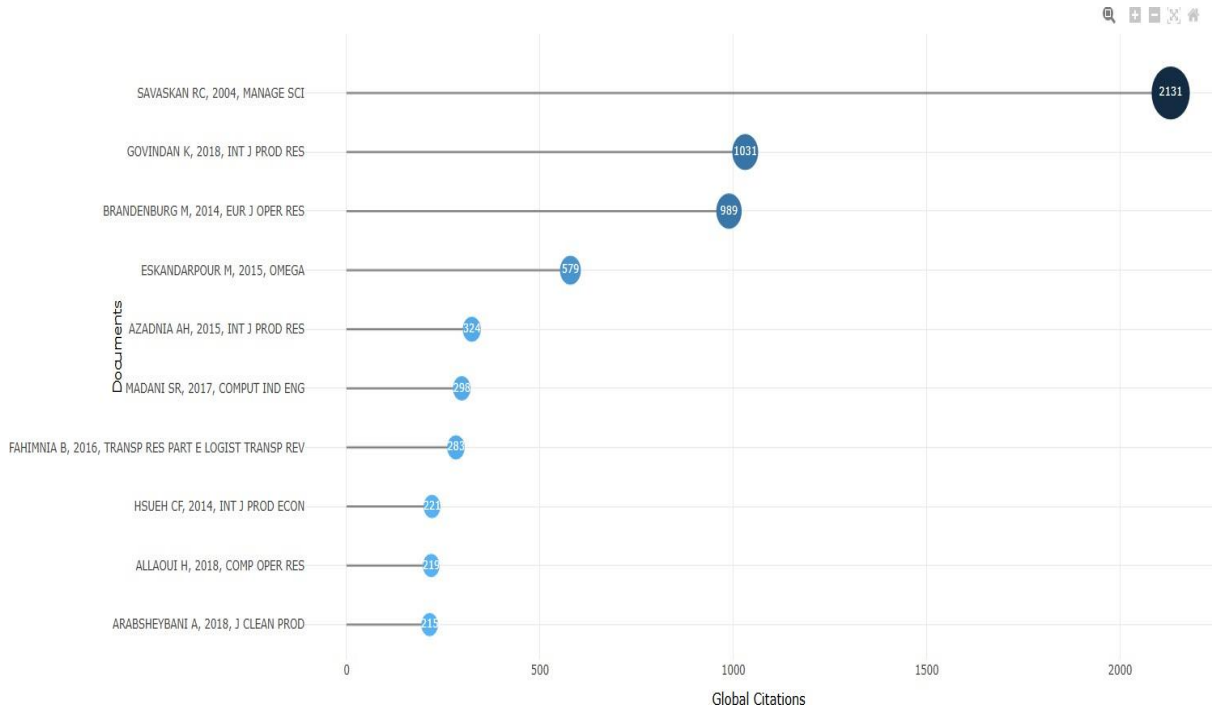

Figure 6: Author wise trends of research papers by R-Studio

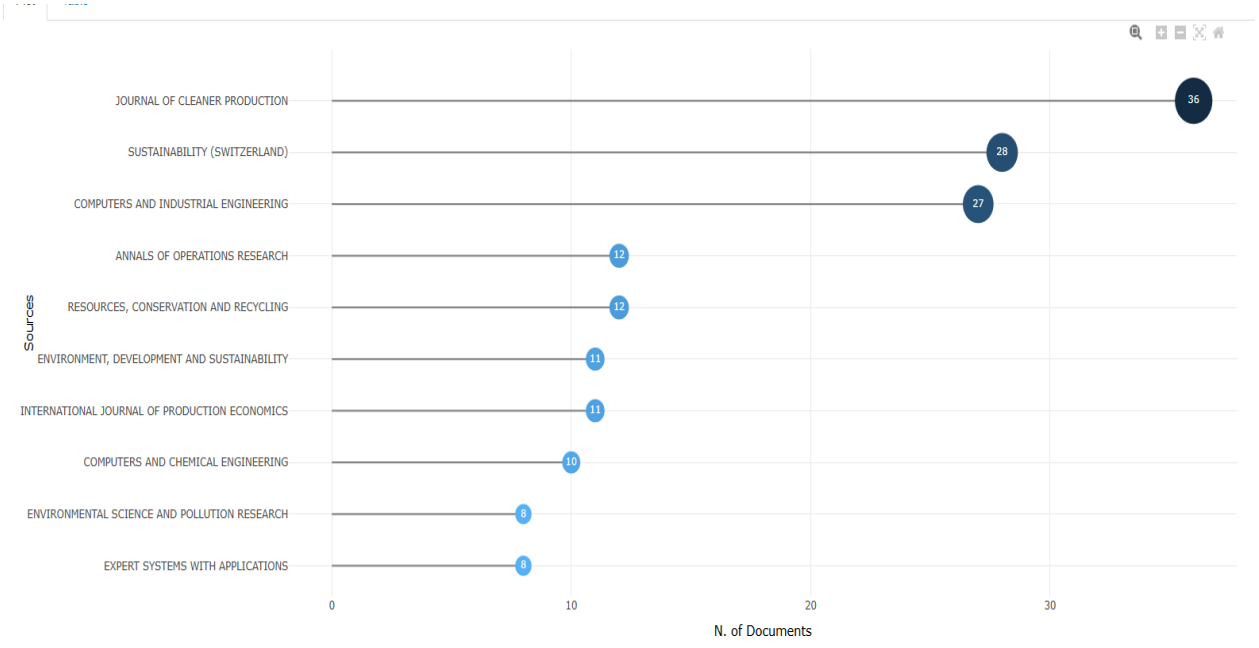

Figure 7: Journal wise trends of research papers by R-Studio

Year wise research papers distribution: In our analysis we collect substantial number of papers, we organise yearly to observe the latest trend in sustainability in recent years. We found that over 50 percent papers have been published since 2021. This Sharp trend shows how optimization techniques are becoming a key player in sustainability.

S. No.	Year	No of papers
01	1995-2000	2
02	2001-2010	50
03	2011-2020	251
04	2021-2025	373

Table 2: Research papers distribution

2.2. Articles related to literature review:

S. No.	Paper Title	Author & Year	Research Area	Findings
t	"Carbon Taxes and India"	"Fisher- Vanden (1997)"	Greenhouse gas emissions	The study analyses three scenarios with restricted greenhouse gas emissions alongside a reference scenario.
2	"Reverse Channel Design, the case of competing retailers"	"Savaskan, (2006)"	Retailers' behavior	Examines the cost-benefit decisions manufacturers face when choosing reverse logistics channels.
3	"Impact of supply chain management practices on sustainability"	"Govindan, k. (2008)"	Studies how social sustainability influences corporate decision-making	The study reviews social impact and initiative metrics, along with relevant indicators and frameworks.
4	"On sustainability, resilience and the sustainable-resilient supply networks"	"Rajesh, R. (2018)"	Association Between Supply Chain and Sustainable Development	The research investigates the connection between SC attributes and sustainable development.

5	"Simulations planning and design of supply chain with reverse flow: A generic modeling framework"	"Salema, M.I.G. (2010)"	Supply chains with reverse flows	The model is designed for the concurrent design and planning of supply chains.
6	"The Supply chain of CO_2 emissions"	"Devis S.J. (2011)"	CO2 emission and carbon tax concept	The analysis focuses on their relation to contemporary energy consumption patterns.
7	"Renewable energy supply chain performance, application barriers and strategies for further development"	"Wee, H.M. (2012)"	Green energy Supply chain	Assesses renewable energy sources from a supply chain perspective Frank.
8	"Evaluating the carbon emissions of the low carbon city: A novel approach for consumer-based allocation"	"Paloheimo (2013)"	Emission of carbon	The findings indicate that the existing assessments fail to present a comprehensive overview of greenhouse gas emission.
9	"Robust solution approach to CLSP problem with an uncertain demand"	"Dangelmaier, W., & Kaganova, E. (2012)"	Supply and demand variability affects	The study investigates the influence of demand & supply uncertainties on the design and planning of a generic multi-product, multi-period CLSP.
10	"Sustainable supply chain management—A conceptual framework and future research perspectives"	"Brandenburg, M. (2019)"	Supply Chain Strategies for Achieving Sustainable Performance	This study proposes a methodology that establishes a link between supply chain choices and sustainable performance.
11	"Environmental policy, sustainable development, governance mechanisms and environmental performance"	"Haque, F., & Ntim, C. G. (2018)"	Design and advancement of eco-friendly products	The study integrates the environmental quality dimension into its analysis.
12	"Evaluating ecological sustainable performance measures for supply chain management"	"Bai, C. (2012)"	Best worst method	The study aims to evaluate environmental standards for sustainability in selected Bangladeshi businesses.
13	"Circular sustainable supply chain management framework from the perspective of triple bottom line"	"Santiago, B., (2023)"	Triple-bottom-line integration in supply chain operations	This study incorporates the concept of sustainability—encompassing economic, social, and environmental dimensions that support an organization's long-term economic viability—into the existing body of literature.

14	"Bio-inspired nanoparticles for artificial photosynthesis"	"Kathpalia, R., & Verma, A. K. (2021)"	Conversion of CO_2 into Green Fuels	This study summarizes the principles and operational methods of converting CO_2 into hydrocarbon fuels using enzymatic techniques.
15	"The scale and drivers of carbon footprints in households, cities and regions across India"	"Lee, J., (2021)"	Climate policy	This analysis suggests that carbon footprint reduction efforts in India should prioritize high-expenditure households Paraskevopoulou.
16	"China's catching-up in artificial intelligence seen as a co-evolution of corporate and national innovation systems"	"Lundvall, B. Å., & Rikap, C. (2022)"	Accountability for different supply chain	The study demonstrates that the supply chain operates as a unified system.
17	"An assessment of circular economy interventions in the peach canning industry"	"Paraskevopoulou, C., (2022)"	Circular Economy, Supply Chain	Research outcome help's farmer to increase income.
18	"Unveiling the green paradigm: Introducing gross environment product (GEP)-The frontier in ecological growth"	"Joshi, A. P., (2013)"	GEP	Developing a GEP index aimed at promoting environmentally sustainable management practices. .
19	"Sustainable performance and supply chain leadership in logistic firms: the role of corporate sustainability strategies and digital supply chain"	"Esangbedo, C. O., (2024)"	Supply chain leadership in logistic firm	Relationship between supply chain leadership, digital supply chain practices and corporate sustainability strategies.
20	"Exploring the potential of industry 4.0 in manufacturing and supply chain systems: Insights and emerging trends from bibliometric analysis"	"Zahid, A., (2025)"	Industry 4.0 in manufacturing and supply chain system	This study indicates a significant an increase in research output, particularly in the integration of IOT, AI and big data analytics.

Table 3: Articles related to literature review

3) Supply chain models utilized in existing research:

Author(s)	Type	Model Type	Objective(s)	Determine
Tsiakis & Shah (2001)	Operational	MILP	Cost minimization	Design of network and product flow quantities
Chen & Lee (2004)	Operational	MINLP	Maximize profit, safety stock, service level, robustness	Planning of production, transportation, pricing, inventory, and sales
Sheu & Shou (2005)	Coordinated	LP	Maximize profitability	Product quantity optimization
Altiparmak & E. Gen (2006)	Operational	MINLP	Minimize cost, capacity imbalance; Maximize service	Network configuration and product allocation
Salema & Barbosa (2007)	Coordinated	MILP	Cost minimization	Product flows, distribution fractions, network structure
Salema & Barbosa (2007)	Coordinated	MILP	Profit optimization	Network and inventory planning, production volumes
Al-Othman & Lababidi (2008)	Operational	LP	Profit maximization	Production schedule, inventory decisions, product quantities
Azaron & Brown (2008)	Operational	MINLP	Minimize investment, cost variance, and risk	Network layout, production planning, product volumes
Liang (2008)	Operational	LP	Reduce cost and delivery time	Production, inventory, backorders, product quantities
Mahnam & Yadollahpour (2009)	Operational	LP	Cost efficiency	Maintain target fill rate
Abdallah & Diabat (2010)	Operational	MILP	Cost reduction	Network layout and product flow decisions
Che & Chiang (2010)	Operational	MINLP	Reduce cost and delays; Improve quality	Material flow, product quantities, transport timing
Franca & Jones (2010)	Operational	MINLP	Maximize profits, minimize supplier defects	Supplier selection, product allocation, network design
Pishvaee & Torabi (2010)	Coordinated	MILP	Minimize cost and delivery delays	Product flows and network strategy

Ramudhin & Chabbane (2010)	Operational	MILP	Cost reduction	Product routing and network structure
Yang & Wee (2010)	Coordinated	NLP	Profit maximization	Production levels, workforce, shortages, product quantities
Al-e-hashem & Malekly (2011)	Operational	MILP	Minimize shortages and losses	Network configuration and product allocation
Cardona-Valdés & Alvarez (2011)	Operational	MILP	Reduce cost and lead time	Product quantities and logistical layout
Giarola & Zamboni (2011)	Operational	MILP	Profit maximization and emission reduction	Number of transport trips
Eskandaepour, et.al. (2013)	Strategic	MILP	Cost emission trade off	Sustainable facility location
Sitek & Wikarek (2015)	Operational	MILP	Timely order execution & cost	Order execution and recycling constrain
Cortinhal, et.al. (2019)	Tactical	MILP	Lowest total network cost	Network configuration and service constrain
Parhazeh, et.al. (2024)	Tactical	Robust MILP	Cost optimization under uncertainty	Supply chain robust planning
Shaerpour, et.al. (2024)	Tactical	MILP	Cost emission social benefit	Circular supply chain planning
Chaudhry & Patnaik (2025)	Review	Multi Objective	Classify supply chain models	Classification of models in textile supply chain
Prasad, K.D. et.al. (2025)	Optimization	Decision Process	Multi objective optimization	Production and delivery trade off

Table 4: Supply chain models utilized in existing research

*Note: OL = Open Loop, CL = Closed Loop, LP = Linear Programming, MILP = Mixed Integer Linear Programming, MINLP = Mixed Integer Non-Linear Programming, SO = Single Objective, MO = Multi Objective.

4) **Research gap:** Study of the research literature finds the following research gaps:

6.1. Traditional Approaches in Supply Chain Modelling.

6.2. Limited Flexibility in Addressing Diverse Business Scenarios.

6.3. Inadequate Integration of Sustainability in Quantitative Models.

6.4. Scarcity of Quantitative Models Addressing Industry 4.0 Integration.

6.5. Urgency in Modelling Carbon Emission Control Mechanisms.

5) **Research objective:**

7.1. The aim of this proposal is to develop a model that will create a direct sustainability design in the existing supply chain model. This design will explain how supply chains impact economic, environmental, and social structure.

7.2. The goal is to formulate a mathematical model using advanced computing tools, which can effectively resolve uncertainty and disruption in modern supply chain networks.

7.3. To develop a mathematical model that will be required in today's supply chain networks, like machine learning and quantum computing.

7.4. To develop an optimization model that will mitigate the challenges of industrialization 4.0. These optimization techniques will help the supply chain to run smoothly by making a balance among cost, service level, limited resources, deadlines and sustainability goals without losing efficiency and effectiveness of SC.

7.5. To develop a model using computer algorithms, which will include carbon offset method and trading of carbon systems inside the supply chain models.

6) Research methodology: This literature review uses systematic optimization techniques to create a sustainable supply chain model by a five-phase study. To fulfil the identified research, gap this method includes literature review, mathematical models, computational algorithm for optimization, validation and policy recommendation for future research.

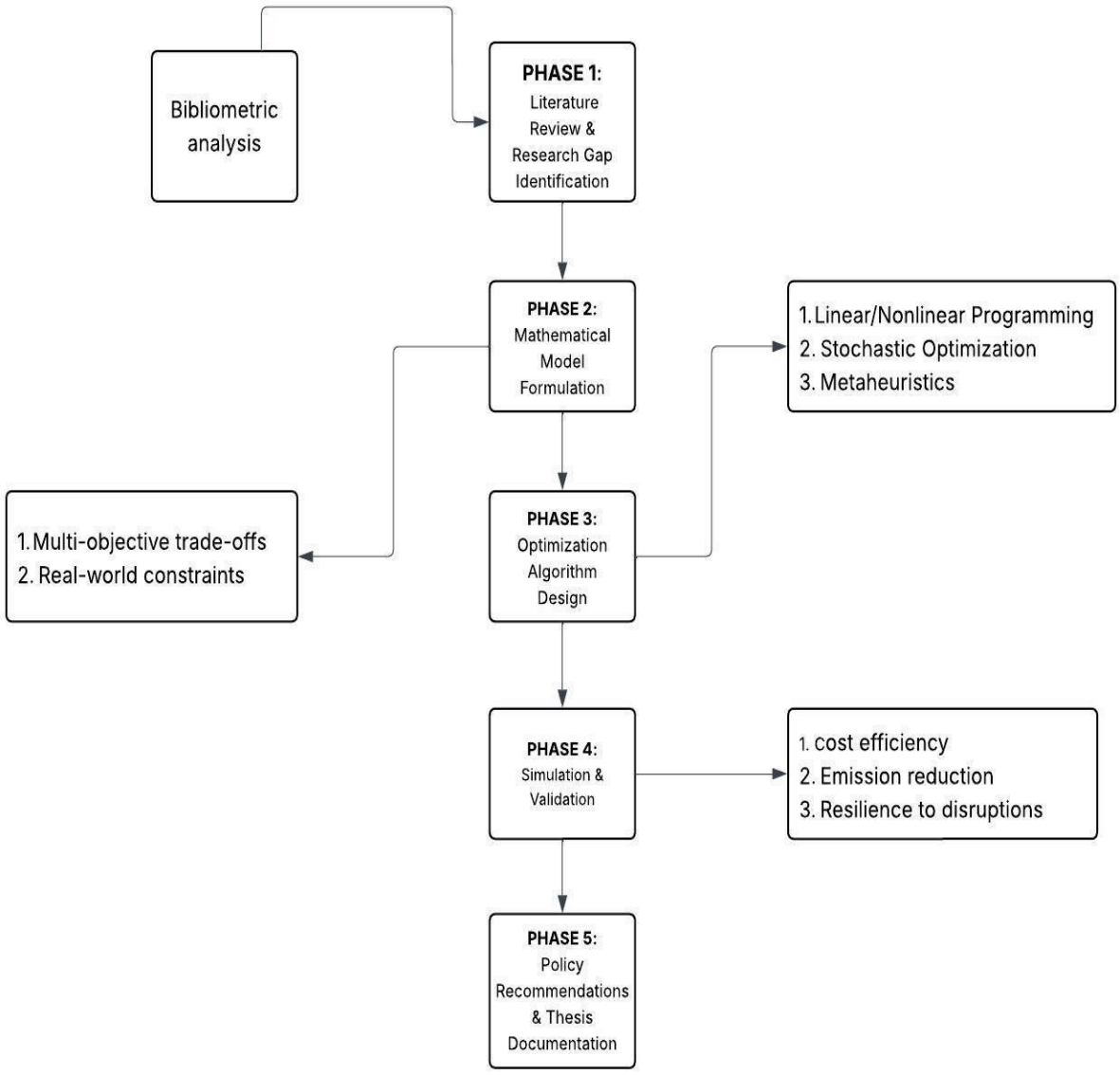
Bibliometric analysis
PHASE 1: Literature Review & Research Gap Identification
PHASE 2: Mathematical Model Formulation
1. Linear/Nonlinear Programming
2. Stochastic Optimization
3. Metaheuristics
1. Multi-objective trade-offs
2. Real-world constraints
PHASE 3: Optimization Algorithm Design
PHASE 4: Simulation & Validation
1. cost efficiency
2. Emission reduction
3. Resilience to disruptions
PHASE 5: Policy Recommendations & Thesis Documentation

Figure 8: Research methodology flow chart

Phase 1: Comprehensive Literature Review and Gap Analysis

- Review existing supply chain models, used optimization techniques and sustainability models and approaches by using bibliometric analysis.
- Differentiate traditional supply chain drawbacks and compare with new requirements.
- Use important variables: CSR, carbon cess, carbon footprints and economic restrictions on carbon producing products.

Phase 2: Dynamic Mathematical Model Development:

- Develop stochastic and deterministic models to solve multi objective trades off problems in supply chain.
- Use probabilistic components to develop risk aware decision.

Phase 3: Design of Optimization Algorithms

- By using MATLAB and Mathematica to solve linear and non-linear problems.
- Develop hybrid algorithm to integrate resources with sustainability and carbon emission.

Phase 4: Computational Experiments and Validation

- Simulate models using industry datasets or synthetic benchmarks.
- Compare performance against conventional SCM models via matrices: Cost efficiency and Emission reduction.

Phase 5: Synthesis and Policy Implications

- Derive actionable insights for businesses and policymakers.
- Document theoretical contributions, limitations, and future research directions.

7) Significance of proposed work: This proposed work "Development of sustainable supply chain models without carbon emission using optimization techniques" fulfill the important gap in today globalized modern supply chain. This work will help to improve important academic, industrial and environmental implication. The important findings and results of this proposed work are following:

9.1. To address the shortcoming of existing supply chain models, this study will develop a new mathematical model using modern technology that incorporate social, economic and environmental sustainability.

9.2. Current supply chain complexities like inflation, supply chain disruption, demand fluctuation, time bound services and sustainability overlooked by existing model. In way to confirm the applicability of the current models this research creates adaptable, flexible and industrial based demand models which will fulfil the industrial 4.0 demand on priority basis.

9.3. Developed model provide industries the best methods to cut-short their carbon emission and produce more environmental product. Which will increase the competitiveness of Indian product on western market where carbon cess is in trends. More environmental product will provide an edge Indian manufacturers in the upcoming carbon trading and offset system.

9.4. This study will help policymakers and legislature to make rules that promote supply chain and produce product which are environmentally friendly.

9.5. This research will help in bringing new models for upcoming supply chain problems and enhance the literature on sustainable supply chain model.

8) <u>Work plan</u>: Proposed semester-wise work plan

GOALS	Year I (2023-24)		Year II (2024-25)		Year III (2025-26)	
	Semester I	Semester II	Semester III	Semester IV	Semester V	Semester VI
Course Work						
Literature Review						
Preparing PhD Title						
Research Publication						
Data Collection						
Data Analysis						
Thesis Proposal						
Pre Ph.D.-Seminar						
Thesis Writing						
Presentations						
Drafting a thesis						
Thesis Completion						
Ph.D. Defense						

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